A Hybrid Actuation System Demonstrating Significantly Enhanced Electromechanical Performance

Ji Su[a], Tian-Bing Xu[b], Shujun Zhang[c], Thomas R. Shrout[c], and Qiming Zhang[c]
[a]NASA Langley Research Center, Hampton, VA 23681
[b]National Institute of Aerospace, 144 Research Drive, Hampton, VA 23666
[c]Materials Research Institute, The Pennsylvania State University, University Park, PA 16802

ABSTRACT

A hybrid actuation system (HYBAS) utilizing advantages of a combination of electromechanical responses of an electroative polymer (EAP), an electrostrictive copolymer, and an electroactive ceramic single crystal, PZN-PT single crystal, has been developed. The system employs the contribution of the actuation elements cooperatively and exhibits a significantly enhanced electromechanical performance compared to the performances of the device made of each constituting material, the electroactive polymer or the ceramic single crystal, individually. The theoretical modeling of the performances of the HYBAS is in good agreement with experimental observation. The consistence between the theoretical modeling and experimental test make the design concept an effective route for the development of high performance actuating devices for many applications. The theoretical modeling, fabrication of the HYBAS and the initial experimental results will be presented and discussed.

Keywords: Hybrid, actuation system, electroactive polymer, electrostrictive, electroactive ceramics, single crystal.

1. INTRODUCTION

Electromechanical actuators have been widely used in many civilian and military applications including active vibration control, aerospace, underwater navigation and surveillance, microphones, etc. [1, 2] as well as flow dynamic control in NASA missions. In many of these applications, actuators with high power and high displacement output are demanded. In the past several decades, a great deal of effort has been devoted to the development of electromechanical materials with those desired features. [3-7] Since Newnham *et.al*.[8] invented the metal-ceramic composite actuators, many device configurations have been exploited for amplified displacement and enhanced performance efficiency.[9] Recently, it was reported that a massive electrostrictive response could be obtained in several kinds of electroactive polymers (EAPs) including poly(vinylidene-fluoride) (PVDF)-based copolymers, terpolymers, and grafted elastomers.[10-13] These electroactive polymers demonstrate a dimensional increase in transversal direction when activated by an electric field while most electroactive ceramics, especially electroactive single crystals, demonstrate the opposite response: a dimensional decrease in transversal direction when activated by an electric field.[14,15] The present work is to develop an electromechanical actuation system utilizing the characterization of the electromechanical performance of these two types of electroactive materials in a cooperative and effective way. A hybrid actuation system (HYBAS) was designed and fabricated using an electrostrictive polymer and an electrostrictive single crystal. [16] The system showed a significantly enhanced electromechanical performance compared to the performances of the device made of each constituting material, the electroactive polymer or the ceramic single crystal, individually. The electromechanical performance of the system also exhibited a good agreement with the theoretical modeling.

2. EXPERIMENTAL

The materials used in this investigation are the uniaxially stretched and high energy electron-irradiated copolymer of vinylidenefluoride-trifluoroethylene, P(VDF-TrFE), as the electroactive polymer component, and the Rhombohedral <001> oriented $Pb(Zn_{1/3}Nb_{2/3})O_3$-4.5%$PbTiO_3$ crystal (<001> oriented PZT-4.5%PT), PZN-PT single crystal, as the electroactive ceramics component. The electroactive polymer film was prepared by a solution casting process. The film was irradiated by an electron beam. A solution cast 68/32 mol% polyvinylidene fluoride-trifluoroethylene [P(VDF-TrFE)] copolymer film was uniaxially stretched to five times its original length at room temperature. The film was annealed at 140°C for 14 hours to increase the Crystallinity, then irradiated by 1.2 MeV electron beam at 100°C with 70Mrad dose for 6 hours. The power of the beam was 3 rad; the irradiation temperature was 60 °C. The single crystal of PZN-PT was grown using the high temperature flux technique. The single crystal beam, oriented along the <001> direction characterized by a Laue Camera[5], was prepared by polishing with silicon carbide and alumina polishing powders to have top and bottom surfaces flat and parallel. Gold electrodes were deposited onto the surfaces by sputtering. The size of the beam was 5(L)x3(W)x0.5(t)mm. Both constituent materials offer high transverse electrostrictive strain. However, the directions of the electric field-induced strain responses from them were opposite transversally.[10,13]

The HYBAS configuration adopted for this investigation is shown schematically in Fig. 1a and Fig. 1b for a side view and an end view, respectively. Two pieces of plastic rod, as a frame to connect the single crystal and the EAP components, were bonded at both ends of the PZN-PT single crystal beam, which was coated with gold electrodes on both top and bottom sides. The effective length of the HYBAS was defined by the length of the single crystal component. The electroactive polymer element used was a bi-layered actuator formed with a 15m thick active layer bonded to an inactive layer (same polymer) with the same thickness. The electroative element was bonded onto both ends of the single crystal beam. The glue used for the bonding was Spurr epoxy (Polysciences, Inc., Warrington, PA)[9]. The inactive layer should act as a direction controller to guide the motion of the EAP actuation element when it is activated electrically. The small gap between the EAP and the single crystal beam was for easy processing control and characterization. The space of the gap can be varied as needed for different applications.

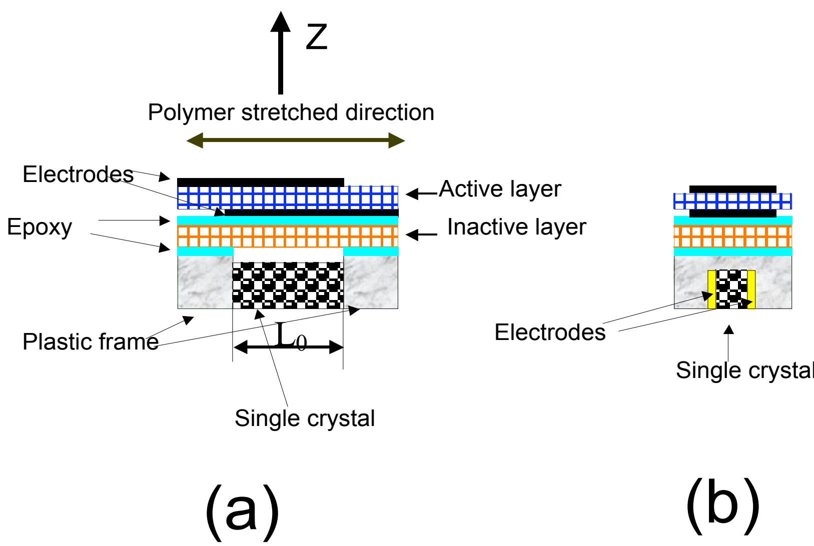

Fig.1. (a) Schematic of the HYBAS investigated. (b) The electrode pattern of the PMAT active polymer (black area) where the electrode width along the x-direction is the same as the device actuation length L_0 in the same direction and along the y-direction, the unelectroded margin width is 0.5 mm to prevent the breakdown at the edges.

According to the theoretical calculation, if a lower modulus or a thinner inactive layer is utilized, the clamp effect should be reduced and the displacement of the HYBAS should be increased. In addition, the thickness ratio and elastic constant ratio between the two polymer layers can be varied to tailor the actuators for different applications. The electric connection of the system was designed and fabricated to allow two components of the HYBAS to be activated at the same time and by the same power supply for reduction in the cost and for increase in the energy efficiency.

The actuation of the HYBAS is schematically shown in Fig. 2. When an electric field (voltage) is applied, the displacement of the actuation system will be generated in the direction perpendicular to the horizontal surface of the device. The displacement response was measured by a laser vibrometer (Polytec PI, Inc., model OFV-512) at room temperature. The size of the laser beam was 5 μm in diameter. The upper measuring frequency was 100 kHz.[14]

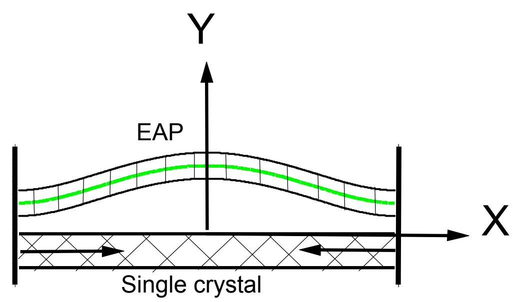

Fig. 2. Schematic of the actuation response of the current PMAT under external fields: because of $S_1>0$, the actuator moves upward from the neutral position (z=0).

3. RESULTS AND DISCUSSION

3.1 Theoretical modeling and analysis

Since the elastic modulus of the single crystal (20GPa)[17] is much higher than the elastic modulus of the polymer (1GPa)[9] and the area of the cross section of the single crystal is 20 times larger than that of the polymer component, the dynamic length of HYBAS L_0' is dominated by the signal crystal component. It can be expressed as:

$$L_0' = L_0(1 - S_{sc}) \qquad (1)$$

where L_0 is the total initial length of the single crystal, ie., the total effective length of the HYBAS at zero electric field, and S_{sc} is electrostrictive strain in single crystal which is a function of electric field.

For the HYBAS investigated here, the displacement along the z direction as a function of x can be expressed as [14, 18]

$$z = a\left[\left(\frac{L_0'}{2}\right)^2 - x^2\right]^2 \qquad (2)$$

The L_0' is determined by equation (1) and the constant a in the equation is determined by the effective strain S_e of the EAP polymer in the film in the x direction and the dynamic length of the HYBAS L_0', i.e.,

$$\int_{-\frac{L_0'}{2}}^{\frac{L_0'}{2}} \left[(\frac{dz}{dx})^2 + (\frac{dx}{dx})^2\right]^{1/2} dx = (1 + S_e)L_0 \qquad (3a)$$

Using Eqs. (1), and (2), Eq. (3a) can be written as:

$$\int_{-\frac{L_0}{2}}^{\frac{L_0}{2}} \sqrt{a^2\left(4x^3 - L_0^2(1-S_{sc})^2 x\right)^2 + 1}\, dx = \left(1 + S_e\right)L_0 \qquad (3b)$$

which is based on the geometric constant that the total length of the polymer actuator component after actuation should be equal to the polymer film length after strain S_e. Because of the inactive polymer layer, S_e is different from strain S_f of the active polymer measured in free condition. It can be determined by [14]

$$S_e = \frac{S_f}{1+k} \qquad (4a)$$

where k is the clamping effect constant due to the inactive layer, the metal electrodes and the edges,

$$k = \frac{\sum E_{ni} t_{ni} b_{ni}}{E_a t_a b_a} \qquad (4b)$$

where E_a, t_a, and b_a are the elastic modulus, thickness, and width of the active layer; and E_{ni}, t_{ni}, and b_{ni} are the elastic modulus, thickness, and width of the *i*th inactive layers; respectively.

Submitting S_{sc}=0 to the equations above, the single contribution of the polymer actuator can be calculated. On the other hand, the single contribution of the single crystal component to the HYBAS can be calculated by assuming strain in the polymer component S_e =0.

3.2 Characterization of the fabricated HYBAS

The displacement profiles of a HYBAS was characterized as a function of driving voltage. Fig. 3a, Fig. 3b and Fig. 3c present the displacement of the device at 200V_{rms} (the electric field of 0.6V/µm for the single crystal element and 16.7V/µm for EAP element), 400V_{rms} (the electric field of 1.2V/µm for the single crystal element and 35.4V/µm for EAP element), and 800V_{rms} (the electric field of 2.4V/µm for the single crystal element and 70.8V/µm for EAP element), respectively. From the same Figures, the displacement profile of the device along the x direction can also be observed. As can be seen, the experimental results (dotted lines) and the theoretical modeling from Equations (1) to (6) (solid lines) are in good agreement. The displacement increases as the electric field applied gets higher. The displacement is dependent on the position in x-axis. The largest displacement is given at the central position and the displacement decreases when the position shifts to the ends of the device. The change of the displacement is symmetric from the central position and the profiles under different electric fields exhibit the same characteristics.

Fig. 4 shows the applied voltage dependence of the displacement from the HYBAS and each constituent active element. The results indicate that the displacement of HYBAS is always larger than the displacement from each individual active element at the same applied voltage. However, the contribution of each active element to the HYBAS depends on the voltage applied. When the voltage is under 300V_{rms}, the contribution from the single crystal element is more significant than that from EAP element, while the contribution from EAP element becomes more significant than that from single crystal element. These results can be interpreted by analyzing the strain-electric field relation, or responsive character, of these two different materials. The electric field-induced strain of an electrostrictive material should follow the relationship expressed by $S = ME^2$, where *M* is the electrostrictive coefficient *and E* is the electric field (E = V/d, where d is thickness of the material). For the single crystal PZN-PT, the electrostrictive coefficient, *M* is larger than that of the EAP at lower electric field and the M decreases as the electric field increases in the electric field range of a few voltage per micrometer (V/µm).[15] Controversially, the electrostrictive coefficient *M* of the EAP, at a lower electric field, is smaller than that of the single crystal. However, the coefficient increases when the electric field is increased. The maximum *M* value for the EAP is given around 70V/µm and stays almost constant up to over 100V/µm.[11] Therefore, at a lower voltage, less than 300V_{rms} for the HYBAS, the strain contribution from the single crystal is higher than that of the EAP. At higher voltage, higher than $300V_{rms}$, the strain contribution from the EAP becomes the dominant one. The cross point of the voltage can be varied by adjusting the electric field ratio of the two components,

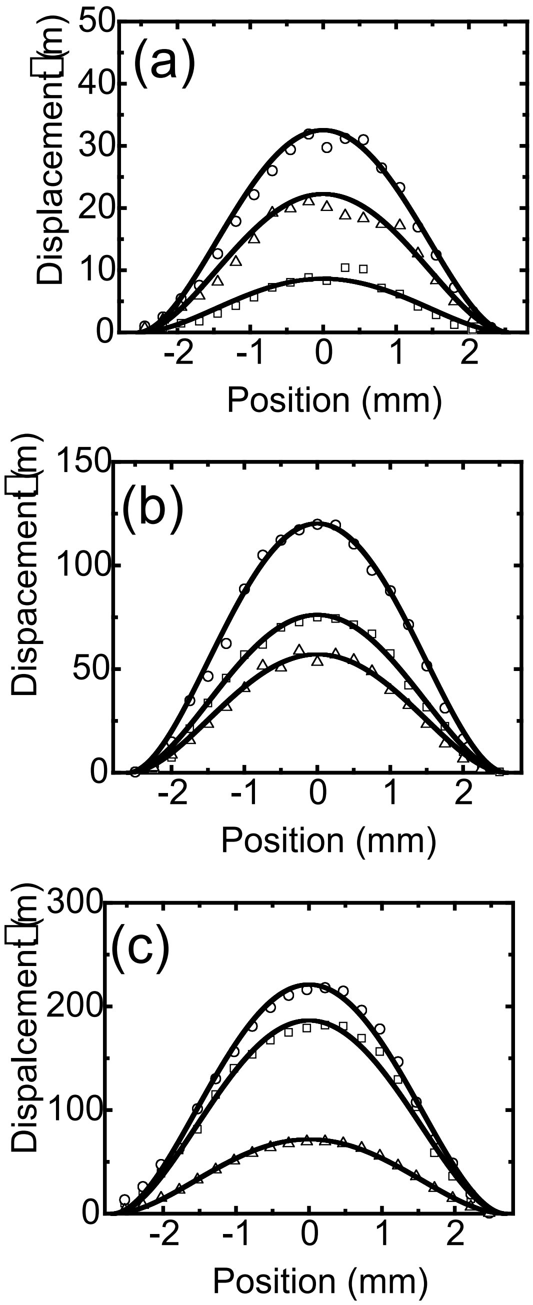

Fig. 3. The displacement profiles on a HYBAS as a function of x for AC driving voltage (10Hz) at: (a) $200V_{rms}$ (Electric field of 0.6V/μm for single crystal and 16.7V/μm for EAP), (b) $400V_{rms}$ (Electric field of 1.2V/μm for single crystal and 35.4V/μm for EAP), and (c) $800V_{rms}$ (Electric field of 2.4V/μm for single crystal and 70.8V/μm for EAP), respectively. The open circular dots are measured displacement for double actuation, the open rectangular for polymer component actuation only, and the open up triangular for single crystal actuation only, respectively. The solid curves are fitting the result from the Eq. (2).

i.e., varying the ratio of the thickness of the two components. It can also be changed by changing the clamp ratio k of the inactive layer of the EAP component. The maximum displacement of the HYBAS is over 220μm at $800V_{rms}$, i.e., electric filed of 2.4V/μm applied to the single crystal and 70V/μm applied to the EAP. Consider the strain-electric field relation of the two materials[9, 15], and the above equation, the maximum displacement of the HYBAS has the capability to reach 400μm.

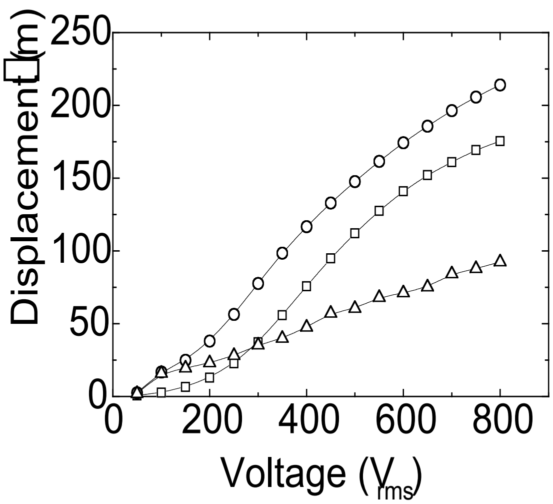

Fig. 4. (a) Displacement at the center of a HYBAS as a function of the applied AC voltage (10 Hz) where dots are the experiment data and solid are guide for eyes. The symbol represented as same as in Fig. 3.

The ratio of contributions from each active element, single crystal or EAP, to the HYBAS is presented in Fig. 5. The reciprocal of the ratio of the contribution will give the ratio of improvement for the HYBAS at the different voltages.

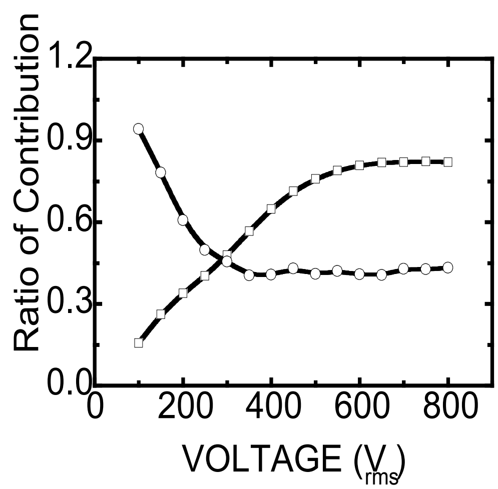

Fig. 5. The ratio of contributions (RC) from each individual element to the HYBAS as a function of applied voltage (open circular dots are for single crystal component and open squares are for EAP component, respectively).

It indicates that the improvement is a few times higher for the HYBAS at lower voltage (or field), either in the EAP-dominated actuation range or in the single crystal-dominated actuation range. It also needs to be pointed out that the ratio of contributions could be tailored by adjusting the ratio of the electric fields on each active component since distribution of the effective fields depends on the thickness ratio of the EAP and the single crystal. This adjustability is an advantage for different applications.

4. SUMMARY

In summary, a high performance hybrid actuation system (HYBAS) was created using an electroactive polymer (EAP), an electrostrictive copolymer and electroactive ceramics, (PZN-PT single crystal). The system was designed and fabricated to utilize the advantages of the combination of the two electroactive materials. A systematic characterization of the developed hybrid actuation system has shown that the electric field activated displacement in the vertical direction is significantly enhanced when compared with actuators made using each single element material individually. The experimental results and modeled results demonstrate good agreement.

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